WOODS HOLE OCEANOGRAPHIC INSTITUTION

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SOME CURRENT MEASUREMENTS IN THE SARGASSO SEA

by

C. Godfrey Day and Ferris Webster

WOODS HOLE, MASSACHUSETTS

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TECHNICAL REPORT

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Some current measurements in the Sargasso Sea*

C. Godfrey Day and Ferris Webster

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Abstract—Long-term current measurements at depths of 50 and 100 m obtained with Richardson current meters at two deep-water moorings south of Bermuda are reported. The records are dominated by anticyclonic rotations which appear and degenerate, possibly in response to the passage of storms. Spectral analysis of the records indicates that this motion has a period of 24 hours at a depth of 50 m, and 25·3 hours at a depth of 100 m. No explanation is given to account for this difference in period over a 50-m separation. Both records indicate the existence of semi-diurnal tidal motion. The long-term motions at both depths indicate a systematic change in the net direction of flow over a three-month period.

COLLECTION OF MEASUREMENTS

In the autumn of 1962, six deep-sea buoy stations equipped with recording current meters, were established along the 65th meridian, south of Bermuda. Mooring failure resulted in the loss of most of this equipment, but three instruments were subsequently recovered. The records obtained are reported.

The moorings and instrumentation were identical to the system described by Richardson (1963), except that 16 m of ½ inch chain was used immediately below the buoy bridle to reduce surges on the cable due to buoy motion. Each current meter was set to record for 1 minute at 20 minute intervals.

Reading of the films was done by eye; signals too weak to be resolved by the electronic method together with blurred rotor counts at the higher current speeds made attempts at automatic read-out unsatisfactory. Subsequent changes in current meter design and in read-out technique appear to have solved these problems.

Webster (1963) analyzed the energy distribution of rotor counts from similar records, but dismissed the directional values because of the wide scatter in vane readings. Similar directional scatter was encountered in the records reported here, particularly at current speeds below 15 cm/sec. In an effort to obviate this difficulty, it was arbitrarily decided to read the directional record once only during each recording interval at the least ambiguous point of the record, this being the spot where both compass and vane appeared to have least motion. It is not possible to assess the consequences of this decision. Such an assessment would require multiple readings, all equally unambiguous during each recording interval over an extended period; the present records do not offer an opportunity for such an analysis because of vane fluttering.

The bulk of the data obtained came from two instruments set at depths of 50 and 100 m on Stn. 101 at 28° 07′N, 65° 02′W, some 250 miles south of Bermuda

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in 5065 m of water. The upper instrument functioned for 85 days from October 10, 1962, through January 3, 1963, following which the vane was alternately jammed or impeded, probably by weed. Upon recovery the vane was found to be in good operating condition, the weed no doubt having been flushed out during retrieval. The lower instrument functioned until recovery on January 27th.

A third instrument, yielding only 5 days of record from October 9th through the 13th, was recovered adrift by HMCS *Nootka*; this was from Stn. 100 which had been set 120 miles to the north at 30° 06′N, 65° 03′W.

Long-term motions

In order to summarize the many observations obtained, the results for Stn. 101 are plotted as progressive vector diagrams (Fig. 1). The directional agreement between the two instruments is excellent up to December 20th. After this the vectors at 50 m turn toward the west and progress cyclonically, making a full circle in 12 days, whereupon the record ends. (There is no indication that the instrument itself was not functioning properly during the final 12 days. Impeded vane movements are easily recognized in these records). During this rotation, the net movement at 100 m continues to be northerly until January 5th, when easterly and then southerly components develop gradually and systematically. Fortunately on January 12th, 14th, and 15th the vane of the upper current meter functioned sufficiently well to allow a rough estimate of direction to be made. Table 1 compares the net directions as recorded by the two instruments on these days. The good agreement lends validity to the extreme change of direction seen at the 100-m level.

Table 1. *Comparison of directions of net daily displacement at two levels at Stn.* 101 *on three days*

	50 m *depth*	100 m *depth*
January 12, 1963	111°T	103°T
14, 1963	100°	105°
15, 1963	106°	128°

Variations in the net daily displacement through December show good agreement between the two levels. From the start of the record in October displacement figures slowly increase until mid-November after which they gradually decrease during the next 30 days. Values range from 0·7 to 16·3 km/day at the 50 m level and from 1·7 to 13·7 km/day at 100 m.

When set out, both current meters were in the seasonal thermocline. At the time of recovery in January the thermocline had been greatly weakened though there remained a slight negative temperature gradient amounting to 0·56° between instruments. Bathythermograph data (WHOI files) indicate that the mixed layer does not extend to 100 m until sometime in February in this region.

From these records it appears that the circulation here is subject to systematic, progressive change. As seen on the 5-day mean sea-level pressure maps covering this period, there is no readily apparent local meteorological cause for the observed change, and no immediate explanation is forthcoming.

The brief 5-day record from Stn. 100 at 30° 06′N is shown in Fig. 2. At this

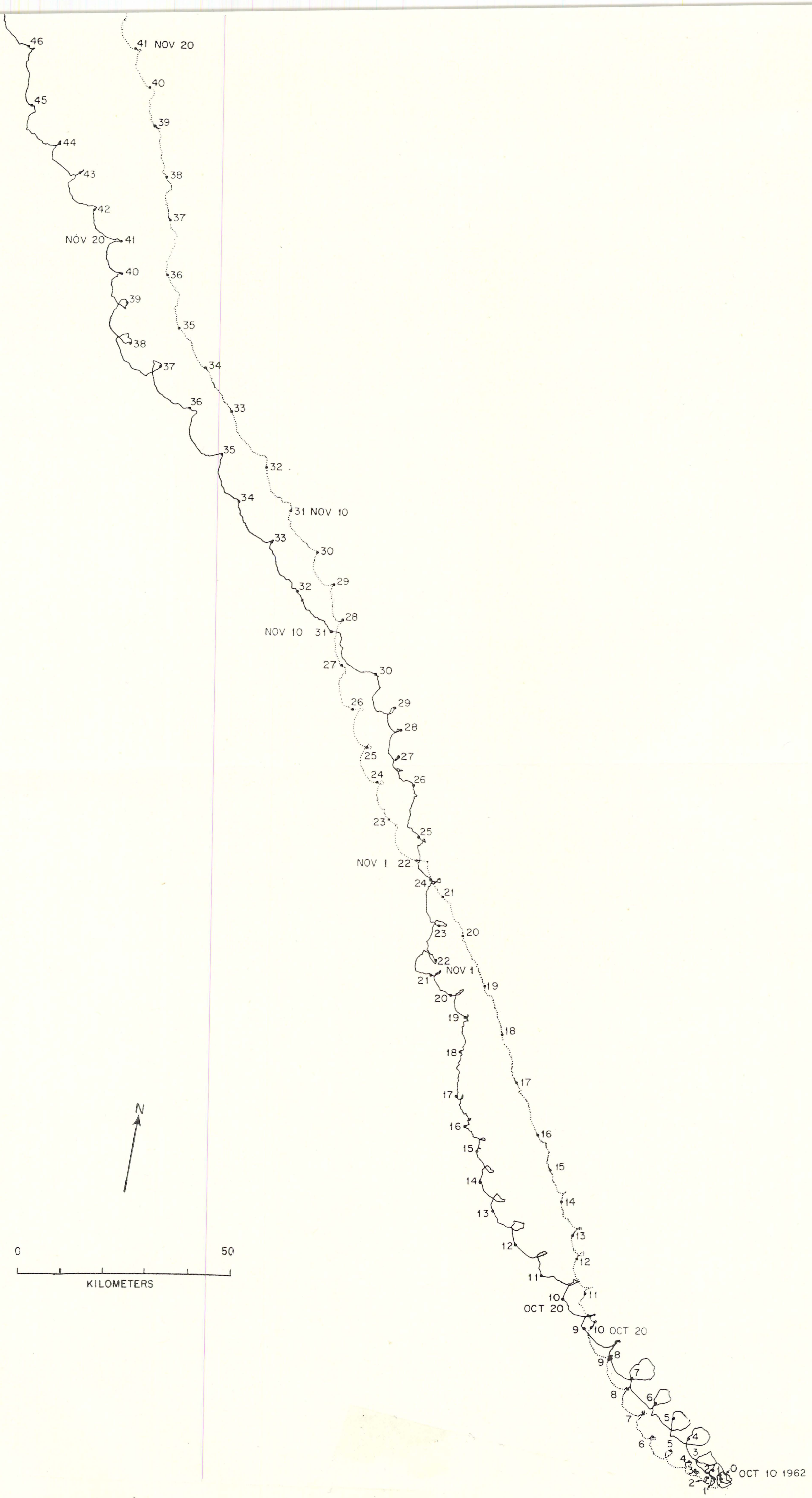

Fig. 1. Progressive vector diagrams from Station 101 (28° 07′N, 65° 02′W) for depths of 50 and 100 m for the period of the records. The diagrams are plotted with 20-min steps, and numbered points correspond to days elapsed since origin at October 10th, 1962. *Solid line*: 50 m; *broken line*: 100 m.

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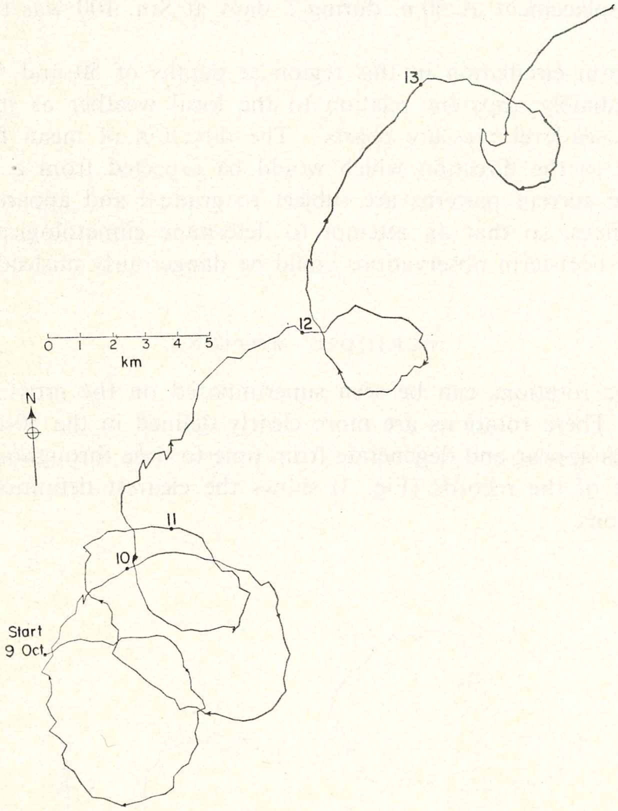

Fig. 2. Progressive vector diagram using values read once every 20 min at a depth of 50 m from Station 100 (30° 06′N, 65°W) for the period from October 9th through 13th, 1962.

latitude the inertial period is 24 hours, but the record is too short to establish the exact period of the observed rotations.

PARKER (1963) describes the track of three drifting buoys, drogued at 1000 m by means of parachutes, during the summer and fall of 1962. The buoys were set out in June at a point 28 miles southeast of Stn. 100 and were tracked from the air in the course of 18 flights until October 17. His results indicate the presence of an anti-cyclonic eddy with its western margin in the vicinity of the 65°W meridian. The net northwesterly movement at Stn. 101 (Fig. 3) and the net northeasterly flow at Stn. 100 (Fig. 2) are in excellent agreement with Parker's deduced circulation in this region.

Current speeds throughout the records at Stn. 101 were averaged for each 10° of azimuth. At 50 m the average values ranged from 16 to 22 cm/sec. Extreme values were 8 and 45 cm/sec. The lower speeds were associated with the rotational movement while the higher had a strong northwesterly component. At the 100-m depth average speeds ran from 13 to 23 cm/sec with extremes of 4 and 44 cm/sec.

The net displacement from October 10, 1962, through January 1, 1963, was towards 329° at 7 cm/sec for the 50-m level and toward 346° at 9 cm/sec at the 100-m level.

The net displacement at 50 m during 5 days at Stn. 100 was towards 044° at 7 cm/sec.

The long-term circulation in this region at depths of 50 and 100 m does not bear an immediately apparent relation to the local weather as interpreted from five-day mean sea-level pressure charts. The direction of mean flow is, in fact, often opposite to the direction which would be expected from a surface Ekman transport. The current patterns are subject to gradual and apparently systematic long-term changes, so that an attempt to determine climatological-mean current patterns from short-term observations could be dangerously misleading.

PERIODIC MOTIONS

Anticyclonic rotations can be seen superimposed on the gross features of the flow (Fig. 1). These rotations are more clearly defined in the 50-m observations, but the motions appear and degenerate from time to time throughout both records. The early part of the records (Fig. 3) shows the clearest definition of these anti cyclonic rotations.

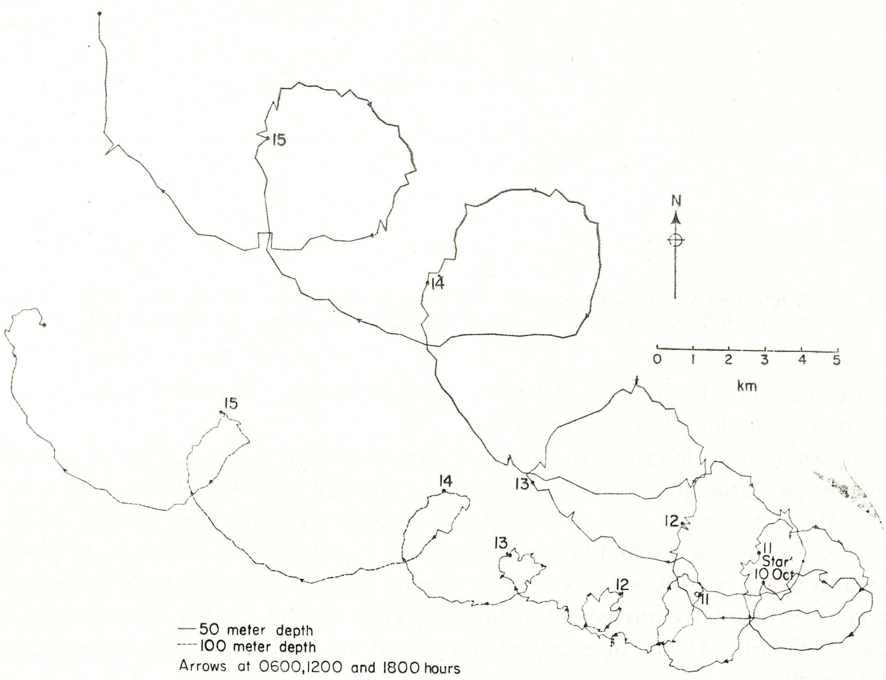

Fig. 3. Progressive vector diagrams from the beginning of the records from Station 101. This portion of the records, following Hurricane Daisy, shows the most clearly-defined periodic motions.

A possible relationship between the passage of storms and the inception of the anticyclonic rotations may exist. The motions shown in Fig. 3, which are the best developed of any in the records, occurred following the passage of Hurricane Daisy the strongest storm during the life of the station. This obvious possible relationship has led to an attempt to discover more general evidence of an air-sea interaction.

Unfortunately, it is difficult to deal with the passage of storms quantitatively; reports of pressure and wind at Station 101 are dependent on passing ships. In the absence of nearby ships, the local meteorological conditions must be interpolated from more distant points of observation, a procedure which necessarily reduces extreme values. Furthermore, no satisfactory objective method has been devised for quantitatively characterizing the strength of distant storms which might affect the ocean currents at Station 101. In the discussion which follows therefore, the treatment of the meteorological effects must remain largely subjective.

For the current meter observations, the amplitude of the anticyclonic rotations as a function of time has been estimated by assuming that these motions have a 24-hour period, and by computing the 24-hour Fourier coefficients for each 24-hour segment of the records. That is, the periodic components of the velocity in the East (X_t), and the North (Y_t) directions are assumed to be of the form :

$$X_t = a_x \cos \frac{2\pi t}{24} + b_x \sin \frac{2\pi t}{24}$$

$$Y_t = a_y \cos \frac{2\pi t}{24} + b_y \sin \frac{2\pi t}{24}\,.$$

where the a's and b's are different for each 24-hour segment. For each 24-hour period, the average kinetic energy of the periodic motion is :

$$\frac{1}{24}\int_0^{24} \tfrac{1}{2}\,(X_t^2 + Y_t^2)\,dt = \tfrac{1}{4}\,(a_x^2 + b_x^2 + a_y^2 + b_y^2).$$

The Fourier coefficients, a_x, b_x, a_y, b_y, are computed for each 24-hour segment of the records by standard methods, namely,

$$a_x = \frac{2}{N}\left\{\tfrac{1}{2}\,(X_0 - X_N) + \sum_{K=1}^{N-1} X_k \cos \frac{2\pi k \Delta t}{24}\right\}$$

$$b_x = \frac{2}{N}\sum_{k=1}^{N-1} X_k \sin \frac{2\pi k \Delta t}{24}\,,$$

where there are N observations in each 24-hour segment, spaced Δt hours apart. Figure 4 shows the kinetic energy of motions with 24-hour period estimated for each 24-hour segment from both the 50 and the 100 m records.

During the period of measurement, several severe storms passed by the region. Hurricane Daisy approached on October 6th, and Hurricane Ella passed by to the west about October 19–20th. A severe North Atlantic storm took place to the north about November 15th, and a storm of nearly hurricane force approached about November 28th, and then lingered to the northward until December 5th. A less strong storm occurred off the east coast of the United States from December 31st to January 2nd. Strong local winds (velocities on daily surface charts exceeding 15 knots) occurred as well on October 29th–November 1st, November 23rd, December 11th, December 29th, January 4–6th, and January 8th. The times of occurrence of these atmospheric disturbances are noted in Fig. 4.

In general, Fig. 4 shows that the occurrence of a storm or strong winds is followed by an increase in the amplitude of the 24-hour period motion at 50 m

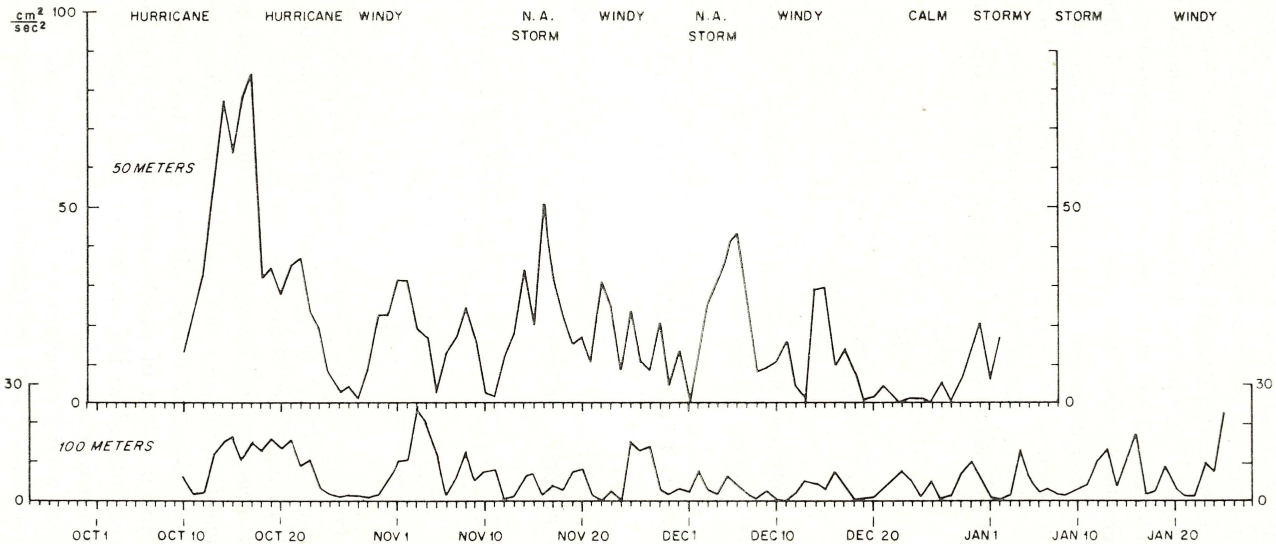

Fig. 4. Kinetic energy of 24-hour-period motions at depths of 50 m (above) and 100 m (below) at Station 101. Along the top of the figure is shown the time of occurrence of various atmospheric disturbances in the region of the measurements. "N. A. Storms" refer to severe North Atlantic storms off the Eastern coast of the United States.

depth. On November 6–8th, the periodic motion was present, but was not preceded by either local winds over 15 knots or a severe North Atlantic storm system. During this period, a frontal system passed over Station 101, and the weather maps, particularly for November 6th, show an ambiguous and confused system. In some other cases, the periodic oceanic motions appear before the occurrence of a local storm. This may be due to the earlier effect of the same storm at more distant locations.

The anticyclonic motions at 100-m depth have a smaller amplitude than at 50-m depth. In addition, the slightly larger net current makes them less clear in Fig. 1. There is, however, no apparent correlation between the inception of the anticyclonic motions at 100-m depth and the passage of storms. Neither is there any apparent coupling with the 50-m depth currents. One might expect that if the anticyclonic motions at the 50-m depth were wind generated their energy would be propagated downward and that at some subsequent time such motions would appear at 100-m depth. No such systematic relationship is apparent.

In order to resolve the periods of the anticyclonic motions more closely, the data were examined using the techniques of spectral analysis. A summary of these techniques, which were first developed by Tukey, is given by MUNK, *et al.* (1959).

The original observations were taken once every twenty minutes : 6120 measurements at 50 m depth, and 7848 measurements at 100 m depth. The north and east components of velocity from

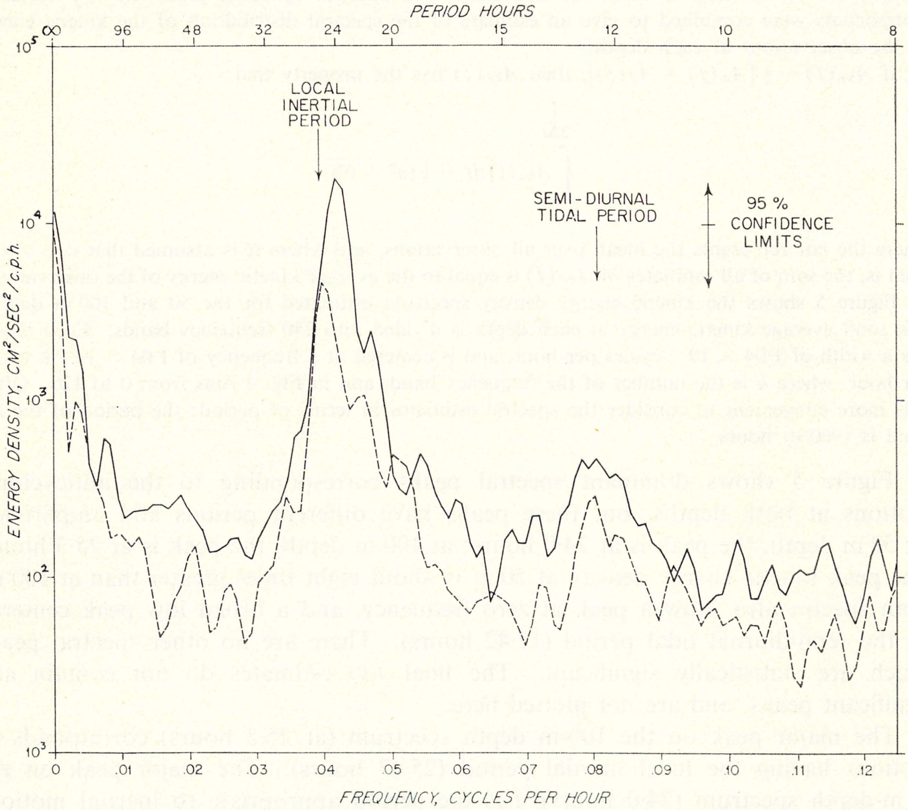

Fig. 5. Kinetic energy density spectra for currents at 50 and 100 m at Station 101. Solid line : 50 m, broken line : 100 m.

each record were handled independently, giving a total of four separate time series. In order to make comparisons more meaningful, the two longer series from 100 m depth were shortened to 6120 terms each, so that only the observations between October 10th, 1962, and January 3, 1963 were used. The number of terms in the series was reduced by averaging in order to enable higher-resolution spectral analysis without expending an inordinate amount of time on the digital computer. Each new averaged value was obtained by forming the arithmetic mean from groups of six consecutive terms of the original series. The averaged series thus consisted of 1040 two-hourly averages of east and north velocity components at each depth.

The method of averaging, which was chosen for its simplicity, can produce aliasing of high frequencies. For a given sampling interval, Δt, the spectrum can be estimated only for frequencies, f, less than the Nyquist frequency, $1/2\Delta t$. All spectral energy at frequencies higher than the Nyquist frequency is folded back into the range $0 \leqslant f \leqslant 1/2\Delta t$. In this range, the higher frequency energy pops up under the " alias " of low frequency energy. The process used here to reduce the number of terms involves first an averaging, which has the effect of filtering out some of the high frequencies, and then a sub-sampling, which has the effect of lowering the Nyquist frequency. If there are any large spectral peaks in the filtered spectrum beyond the new Nyquist frequency (in this case if there are peaks at periods less than 4 hours) these might be aliased into the final estimated spectra. Preliminary test spectra before averaging did not indicate that such peaks existed here. It is unlikely that the spectral results on which the later discussion is based are affected by aliasing, but this possibility should be borne in mind, particularly when considering smaller spectral peaks for which no physical cause is apparent.

The spectra of the East-component of velocity, $A_u(f)$, and the North-component of velocity, $A_v(f)$, were estimated over 240 frequency bands. The Hanning spectral window (BLACKMAN and TUKEY, 1959) was used to form the estimates. The spectral estimates from the two cartesian components were combined to give an estimate of the spectral distribution of the kinetic energy of the observations at each depth.

If $A_{ke}(f) = \frac{1}{2}[A_u(f) + A_v(f)]$, then $A_{ke}(f)$ has the property that:

$$\int_0^{\frac{1}{2\Delta t}} A_{ke}(f)\,df = \tfrac{1}{2}\,\overline{(u^2 + v^2)},$$

where the bar represents the mean over all observations, and where it is assumed that $\bar{u} = \bar{v} = 0$. That is, the sum of all estimates of $A_{ke}(f)$ is equal to the average kinetic energy of the observations.

Figure 5 shows the kinetic energy density spectrum estimated for the 50 and 100 m depths. The total average kinetic energy at each depth is divided into 240 frequency bands. Each band* has a width of $1{\cdot}04 \times 10^{-3}$ cycles per hour, and is centered at a frequency of $1{\cdot}04 \times 10^{-3}\,k$ cycles per hour, where k is the number of the frequency band, and in Fig. 4 runs from 0 to 120. Often it is more convenient to consider the spectral estimates in terms of period; the period of the k^{th} band is (960/k) hours.

Figure 5 shows dominant spectral peaks corresponding to the anticyclonic motions at both depths, but these peaks have different periods and amplitudes. At 50 m depth, the peak is at 24·0 hours; at 100 m depth, the peak is at 25·3 hours. The peak kinetic energy density at 50 m is about eight times greater than at 100 m. Both spectra also show a peak at zero frequency, and a broad low peak centered on the semi-diurnal tidal period (12·42 hours). There are no other spectral peaks which are statistically significant. The final 120 estimates do not contain any significant peaks, and are not plotted here.

The major peak on the 100-m depth spectrum (at 25·3 hours) corresponds to motions having the local inertial period (25·47 hours). The major peak on the 50 m-depth spectrum (24·0 hours), has the period appropriate to inertial motions

*The band width of the first and last frequency bands is half that of the others, vis $0{\cdot}52 \times 10^{-3}$ c.p.h.

at a latitude of 30°. Since the measurements were collected simultaneously by current meters having only a 50-m vertical spacing, the difference between the spectra computed from them is surprising. Such a difference might arise from a fast or slow film advance mechanism in one of the current meters. This possibility must be excluded because both spectra show a peak at the period appropriate to the semi-diurnal tide. If either instrument had a film transport motor off by enough to account for the discrepancy in the period of the major peaks, a large discrepancy would be evident between the period of the semi-diurnal tidal peaks. The possibility that film transport might account for the dissimilarity in the spectra is further ruled out by the film record length : both films are within a fraction of an inch of the lengths corresponding to the times during which they were operating.

The general level of the energy density spectrum (Fig. 5) is greater at 50 m depth. The action of wind and waves on the surface float produces mooring noise which appears as fluctuations on the current meter records, and which should be most noticeable on the record from the uppermost current meter. The spectral effect of this noise is to give a fairly constant background value to the spectral density across the entire width of the spectrum and to mask small-amplitude spectral peaks.

In order to test the reality of the apparent difference between the periods of the anticyclonic motions at the two depths, cross-spectral calculations were made. Cross-spectra were estimated between all possible pairs, using the four time series of cartesian velocity components, to give a total of six cross-spectra. Additionally, the cross spectrum between the series of speeds from the two current meters was estimated. Each cross spectrum was estimated over 60 frequency bands, using 1040 two-hourly averaged values. The detailed results of these computations are not shown graphically here, since they can easily be summarized.

In the inertial-period region of the spectrum, no coherence was found between different current meters. The cross-spectra between the cartesian velocity components of the same current meter indicate a high coherence (nearly unity) in the band of frequencies around the period of the observed anticyclonic motions. This coherence results from a normalized quadrature spectrum which is nearly unity, and a cospectrum which is zero, within the significance of the estimates. Such a result is consistent with a well-organised, nearly circular anticyclonic motion. The circles which such a motion would exhibit on a progressive vector diagram are not clearly apparent in Figure 1 because of the added effects of the mean current.

At the semi-diurnal tidal period, a small peak in the cross-spectral coherence was observed between the series of speeds at 50 m and 100 m. This peak (0·28) did not exceed the 5% probability level for zero coherence (0·42) however. That such a peak, if real, was not found between the corresponding series of cartesian components at the two depths may be due to the degradation of the directional measurements by mooring noise. That is, the speeds are far less affected by the mooring noise than are the directions. Mooring noise may also account for the very low coherence between the cartesian components from the same current meter at the semi-diurnal period. The semi-diurnal tidal motions may have too low an amplitude to be discernable above the mooring noise level. Only in the case where the directions are not involved in the data does any recognizable cross-spectral coherence appear.

A significant coherence was found at long periods, near zero frequency, for all cross-spectra between series from the two different depths. This long-period coherence reflects the gross similarity in the two records displayed in Fig. 1.

The results of the spectral investigations may thus be summarized : there are clearly developed motions in the inertial-period range of the spectra from both 50 and 100 depths. These motions, however, have different periods and amplitudes at the two depths. At 50 m, the motion has a period of 24·0 hours; at 100 m, the motion has a period of about 25·3 hours, nearly that of the local inertial period of 25·47 hours. All evidence points to the reality of this difference in the observations collected.

The periodic motions at 50 and 100 m, though superficially similar, are apparently fundamentally different. The 50-m measurements show apparent correlation between the amplitude of the periodic motions and the passage of atmospheric storms. However, the reason for the 24-hour period at 50 m is unclear : it might be due to a diurnal component in the wind stress; it might also be due to some kind of resonant amplification produced by interactions between diurnal tides and inertial motions at 30° latitude. The 100-m periodic motions appear to be local inertial currents.

The mechanism accounting for the periodic motions is an unresolved puzzle. The present observations are unsuited for further analysis, but they do provide some guides for further investigations. More current measurements from the surface layers of the ocean are needed. These should be accompanied by surface wind measurements, and should be arrayed over sufficient latitudinal extent to enable a clear spectral resolution between diurnal and local inertial periods.

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1. Ocean current measurements
2. Sargasso sea
3. Air-sea interaction
4. Inertial-period motions

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